

# Soil management alters seedling emergence and subsequent autumn growth and yield in dryland winter wheat–fallow systems in the Central Great Plains on a clay loam soil

Gregory S. McMaster<sup>\*</sup>, Daniel B. Palic, Gale H. Dunn

USDA-ARS, Great Plains Systems Research, P.O. Box E, Fort Collins, CO 80522, USA

Received 1 December 2000; received in revised form 31 October 2001; accepted 3 December 2001

## Abstract

Stand establishment and subsequent autumn development and growth are important determinants of winter wheat (*Triticum aestivum* L.) yield. Soil management practices change soil properties and conditions, which alter seedling emergence, crop development and growth. Pre-plant soil management practices were studied for 6 years in a wheat–fallow rotation in eastern Colorado, USA, to isolate the impacts of pre-plant tillage (PT) and residue level on winter wheat seedling emergence and autumn development and growth. A split plot design was used with PT, using a moldboard plow that incorporated surface residue, and with no-tillage (NT). The tillage systems represented the main plots and three residue levels within each tillage treatment as subplots: no residue (0R), normal residue (1R) and twice-normal residue (2R). Residue amount had little effect on emergence or autumn growth and development. PT resulted in soil water loss from the plow zone. NT plots had more favorable soil water levels in the seeding zone which resulted in faster, more uniform and greater seedling emergence in 4 out of the 6 years. This is especially critical for stand establishment in years with low rainfall after planting. Soil or air temperature did not account for differences among treatments. Earlier and greater seedling emergence in NT treatments resulted in greater autumn development and growth. Shoot biomass, tiller density and leaf numbers were greater in NT, and again residue amount had little effect. At spring green-up, NT treatments had greater soil water in the profile. Grain yield was always equal or greater in NT than in PT, and positively correlated with earlier/greater seedling emergence and autumn growth. NT will enhance soil protection and likely increase snow catch, reduce evaporation and benefit yield in semiarid eastern Colorado. Published by Elsevier Science B.V.

**Keywords:** Wheat; *Triticum aestivum*; Seedling emergence; Tillage; Residue cover

## 1. Introduction

Farmers are adopting alternative tillage practices for several reasons including economic and soil and

water conservation benefits. Further, farmers must protect their soil from erosion to participate in US federal programs (McMaster and Wilhelm, 1997a). Cereal grain yield response to low- and no-tillage (NT) practices is variable in USA (Aase and Reitz, 1989; Bond et al., 1971; Chevalier and Ciha, 1986; Ciha, 1982; Rao and Dao, 1996; Rasmussen et al., 1997; Unger and McCalla, 1980; Wilhelm et al., 1989).

<sup>\*</sup> Corresponding author. Tel.: +1-970-490-8340;  
fax: +1-970-490-8310.  
E-mail address: greg@gpsr.colostate.edu (G.S. McMaster).

Higher yields are usually attributed to increased water conservation or utilization by the crop, especially for arid and semiarid regions, and lower yields to greater disease and weed infestations and N immobilization, decreased light intensity and quality, and altered rooting patterns and soil temperature.

Tillage practices, with associated effects on residue cover and architecture, affect canopy and soil light, temperature, water and nutrient conditions (Aiken et al., 1997; McMaster et al., 2000; Rao and Dao, 1996; Van Doren and Allmaras, 1978; Wilhelm et al., 1989), and changes in these fundamental factors may provide explanations for the conflicting yield responses observed. Soil water and temperature are two major factors affecting seedling emergence (Studdert et al., 1994; Wilhelm et al., 1993). In regions such as the Central Great Plains, the recommended planting date is mid-September, and stand establishment is highly dependent on subsequent September and October rains to provide sufficient moisture for seed imbibition and germination. Earlier stand establishment favors root and canopy development, especially tillering. Increased autumn growth results in greater root exploration for limited water and nutrients; increased tillering is particularly important in that spike number per unit area is the main yield component in the Central Great Plains (McMaster, 1997; McMaster et al., 1994). Canopy development also positively impacts soil and water conservation during the autumn and winter (McMaster and Wilhelm, 1997a; McMaster et al., 2000) and snow catch during the winter (Greb, 1980). At least 50–70% of the snow captured during the winter is stored in the soil and available for crop use during spring (Greb, 1980), and greater canopy development and residue levels should increase snow catch and recharge efficiency. As potential yield is largely determined near the growth stage of jointing (late April–early May), enhanced soil water conservation in the spring is critical for semiarid regions (McMaster, 1997).

As adoption of reduced- and NT practices increases in the semiarid Great Plains, much work has been done on the impacts of soil management practices on soil factors (Dao and Nguyen, 1989; Ellis et al., 1977; Rao and Dao, 1992; Smika and Ellis, 1971; Wilhelm et al., 1989), but isolating the separate roles of tillage and residue amount on winter wheat seedling emergence, autumn development and growth, and results on final

yield have received considerably less attention. The objective of this work was to contrast the effects of pre-plant tillage (PT) with NT and different residue levels within each tillage practice on seedling emergence and autumn development and growth of winter wheat in a semiarid dryland production system, and relate seedling emergence and autumn growth to final yield.

## 2. Materials and methods

### 2.1. Study site

A 6-year study, beginning in autumn 1992, was conducted northeast of Fort Collins, CO, USA, at the Colorado State University Horticulture Farm (40°36'N, 104°59'W) on a Nunn clay loam soil (fine, smectitic, mesic, Aridic Argiustoll; FAO, Luvic Chernozem). Winter wheat was grown in a wheat–fallow rotation. Previous cropping history was primarily irrigated continuous wheat, with 1 year in alfalfa and 1 year in dry bean crop. Moldboard plow and roller harrowing was used for all crops.

### 2.2. Experimental design and tillage treatments

Treatments were arranged in a split plot design, with tillage being the main plot and residue rate being the subplot, in four replications. Plot size was 6 m × 15 m. Tillage treatments consisted of either NT or a PT treatment of moldboard plow and roller harrowing in all years and additional disking in 1992. Tillage depth was approximately 21 cm. Within each tillage treatment, three different surface residue levels were tested: surface residue removed (0R), normal residue (1R) and twice-normal residue (2R). Residue was hand-raked, weighed and moved from the 0R plots and added to the 2R plots. For PT plots, residue was incorporated into the soil to an approximate depth of 21 cm with the moldboard plow prior to planting. Surface residue gathered in the 0R treatments just prior to planting after approximately 14 months in fallow were 2.7, 4.9, 2.2, 2.0 and 2.2 t ha<sup>-1</sup> for 1992, 1994, 1995, 1996 and 1997, respectively, with a mean of 2.8 t ha<sup>-1</sup> for 5 years (residue for 1993 was not measured). These estimates are approximate because not all surface residue could be gathered and some soil

(approximately 20% of the sample) was included when hand-raking.

### 2.3. Cultural practices

Soil cores (5.7 cm diameter) to 180 cm depth in each plot (24 total) were taken to test for nutrient levels at planting each year. Soil tests indicated that all nutrients were well above recommended levels, so no fertilizer was added except for 1997–1998. In the autumn of 1997, liquid fertilizer was applied with the seed during planting at a rate of 38 kg N ha<sup>-1</sup> as 32% urea ammonium nitrate solution and 9.5 kg P ha<sup>-1</sup> as liquid ammonium polyphosphate (10–34–0). A hard red semidwarf winter wheat (cv. TAM 107) was planted using a double disk drill with coulters in 30 cm row spacing with sowing rate of about 170 seeds m<sup>-2</sup>. Planting depth was between 4 and 7 cm, with depth tending to be slightly greater in the PT treatments. Seeding below 7 cm is generally not recommended as TAM 107 has a relatively short coleoptile length and deeper depths will negatively impact seedling emergence. Planting dates were 9 September 1992, 30 September 1993, 14 September 1994, 12 September 1995, 15 October 1996 and 12 September 1997. Mid-September planting dates are the usual time of planting for this region; the 15 October planting date was late due to equipment problems, but not rare in the region. An accidental irrigation of about 20 mm was applied on 8 October 1992. Standard chemical fallow practices were followed, with occasional broad-leaf weed control applications (usually once a growing season) applied in the spring or summer on cropped plots.

### 2.4. Plant and soil measurements

Seedling emergence was observed at least every 2 days, weather permitting, with two subsamples per plot, where a subsample consisted of 1 m of row. Each subsample, or 1 m of row, was repeatedly observed. Main stem leaf number (Haun, 1973), biomass of leaf blades and stems + sheaths + crowns, plant density and tiller number were measured in early December for most years. Final grain yield was measured with a plot combine.

Soil temperature at 2.5 cm depth (approximate crown depth) was obtained with copper constantine

thermocouples starting in 1994. Nine thermocouples were connected in parallel to give a mean per plot. Automated readings were taken each minute and daily maximum and minimum temperature measured and average temperature was calculated. Soil water was measured using neutron probe (attenuation) for 0–15, 15–30, 30–60, 60–90, 90–120 and 120–150 cm depths with one access tube per plot. Measurements were taken weekly during the autumn. Additional cores (57 mm diameter) from the top 15 cm were collected for gravimetric soil water measurements. Cores were taken 27 (1992), 7 (1993), 6 (1994), 0 (1995) and 1 (1996) day(s) after planting and oven dried at 105 °C. Only in 1992 did rainfall occur (9.7 mm) between planting and measurements. Weather data were collected from a Class A weather station at the site.

Air and soil growing degree-days (GDDs) were calculated according to Method 1 of McMaster and Wilhelm (1997b):

$$\text{GDD} = \frac{1}{2}(T_{\max} + T_{\min}) - T_{\text{base}} \quad (1)$$

$$\text{If } \frac{1}{2}(T_{\max} + T_{\min}) < T_{\text{base}}, \text{ then set equal to } T_{\text{base}} \quad (2)$$

and  $T_{\text{base}}$  is equal to 0 °C (McMaster and Smika, 1988).

Several assumptions were made to estimate the rainfall required for germination based on soil water content at planting to offset the loss of water due to PT. These assumptions for the Nunn clay loam soil, used in the experiment, were: (1) total soil pore space after tillage was 50% (unpublished data), (2) gravimetric soil moisture content for –0.033 MPa (field capacity) was 35% (unpublished data), (3) a planting depth of 5 cm and (4) cumulative rainfall events on soil water content were ignored. The assumption of ignoring cumulative rainfall events seems reasonable given the high evaporative rate at this time of year (up to 10 mm per day), the rarity of successive rainfall events in September and October (data not shown), and usually the daily rainfall events were sufficient for germination. Fig. 1 gives some indication of daily precipitation events in September and October and the reasonableness of this assumption. With these assumptions, rainfall events of 3.8 and 5.1 mm were required to increase the soil water content from 30 or 40% water filled pore space, respectively, to field capacity providing sufficient water for germination

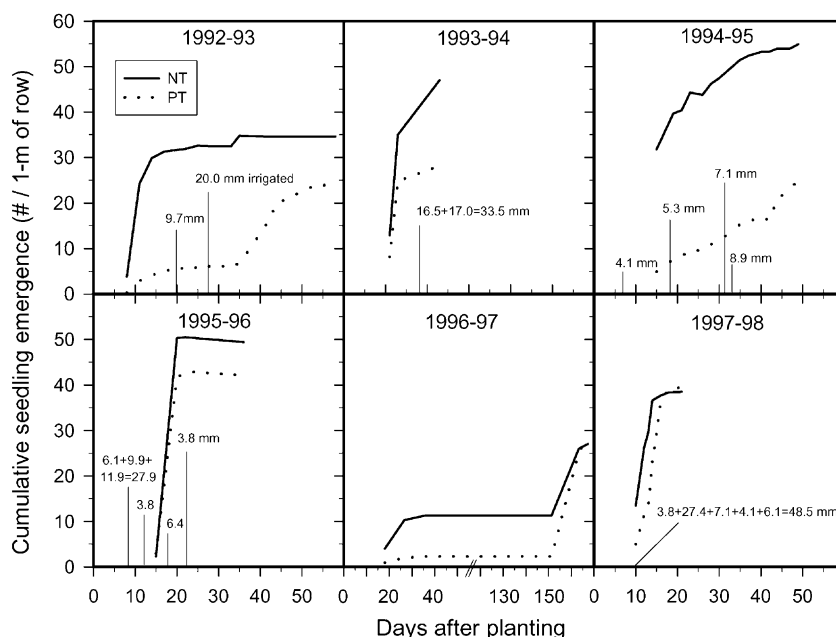


Fig. 1. Seedling emergence over time (in days after planting) when pooling residue treatments within tillage treatments. Table 2 presents the statistical results. Timing of rainfall events are shown by lines with the 24 h amount noted. If rainfall occurred on consecutive days, rainfall for each day is listed and the line is for the mean day. Approximately 55 seeds were planted in 1 m of row.

(Studdert et al., 1994; Wilhelm et al., 1993). The two levels of soil water content (30 and 40%) were chosen to have two different levels of initial soil water content that is typically observed at the time of planting.

The SAS statistical program (SAS Institute, 1991) was used for all data analysis. Analysis of variance, Tukey and LSD used the general linear model (PROC GLM).

### 3. Results and discussion

#### 3.1. Seedling emergence

Considerable climatic variability occurred during this experiment (Table 1). Combining autumn and winter precipitation (August–March), 2 years were within 10% of the 14-year mean (1992–1993 above and 1995–1996 below), 2 years were significantly less than the 14-year mean (1994–1995, 41 mm, 26%; 1996–1997, 50 mm, 31%) and 2 years were greater (1993–1994, 24 mm, 13%; 1997–1998, 25 mm, 14%) than the 14-year mean. In 1992 and 1994, precipitation

in September was significantly below the 14-year mean, whereas in 1993, 1995 and 1997, precipitation was well above normal. Temperature also differed among years both for the autumn/winter period and in September (Table 1). Temperature and precipitation were inversely correlated so that September 1992 and 1994 was hot and dry and September 1993 and 1995 was cool and wet. September 1996 was approximately normal, but a little dry in October when planted, and September 1997 was the exception to the pattern by being hot and wet.

Seedling emergence patterns varied over time (Fig. 1). Whether considering the beginning date of seedling emergence, date of 50% emergence or final number of seedlings emerged, there were no significant interactions between tillage and residue levels (Table 2). Residue levels did not have an effect on the beginning of seedling emergence, date of 50% seedling emergence or final number of seedlings in any treatment except for 50% seedling emergence in 1997 (Table 2). Therefore, results are presented and discussed in terms of tillage treatment effects averaged over the three residue treatments.

Table 1  
Monthly average temperature and precipitation summaries for Colorado State University Horticulture Farm

Month	14-year mean <sup>a</sup>		1992–1993		1993–1994		1994–1995		1995–1996		1996–1997		1997–1998	
	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)	Temperature (°C)	Precipitation (mm)
August	19.5	28	18.9	79	18.6	23	20.5	32	21.1	7	19.0	8	18.8	74
September	15.0	31	17.2	3	13.2	67	16.1	11	13.9	52	13.8	36	16.1	51
October	8.8	19	11.7	11	7.7	43	9.0	34	7.5	7	8.8	9	8.2	14
November	2.2	19	−0.8	24	−0.4	22	1.7	8	3.3	10	1.2	13	0.3	6
December	−2.8	8	−7.2	16	−1.3	4	−0.8	7	−1.1	2	−1.1	2	−1.8	0
January	−2.8	10	−6.9	9	−1.4	8	−1.6	3	−5.0	19	−5.4	18	−1.3	0.5
February	−0.6	12	−3.9	14	−3.0	12	0.9	15	−1.3	5	−1.4	11	0.1	8
March	3.5	32	4.6	21	5.1	4	3.9	8	1.2	42	3.7	12	1.7	30
April	7.9	22	7.5	50	8.5	32	6.1	42	8.4	24	4.7	49	7.1	36
May	13.1	60	13.4	28	15.3	39	9.8	131	13.0	79	12.4	28	13.5	48
June	18.3	46	16.8	49	24.5	35	16.4	69	18.3	46	18.2	36	15.4	30
July	20.4	36	19.6	26	19.8	25	20.6	35	20.3	43	20.1	43	20.9	33
Mean/total (September–November)	8.7	69	9.4	38	6.8	132	8.9	53	8.2	69	7.9	58	8.2	71
Mean/total (August–March)	5.4	159	4.2	177	4.8	183	6.2	118	5.0	144	4.8	109	5.3	184
Mean/total (August–July)	8.5	323	7.6	330	8.9	314	8.6	395	8.3	336	7.8	265	8.3	331

<sup>a</sup> Only 14 years available at this site.

Table 2

Statistical results for the beginning date, date of 50% seedling emergence and final number of seedlings

	1992–1993	1993–1994	1994–1995	1995–1996	1996–1997	1997–1998
<i>Beginning date of seedling emergence</i>						
Tillage	<i>0.01<sup>a</sup></i>	0.11	<i>0.03</i>	0.82	<i>0.01</i>	<i>0.02</i>
Residue	0.35	0.10	0.27	0.25	0.99	<i>0.01</i>
Tillage × residue	0.06	0.30	0.60	0.22	0.43	0.56
<i>Date of 50% seedling emergence</i>						
Tillage	<i>0.02</i>	0.42	0.06	0.22	0.09	<i>0.01</i>
Residue	0.24	0.10	<i>0.03</i>	0.62	0.76	0.10
Tillage × residue	0.45	0.10	0.68	0.26	0.79	0.97
<i>Final number of seedlings</i>						
Tillage	<i>0.05</i>	<i>0.04</i>	<i>0.00</i>	<i>0.01</i>	0.65	0.81
Residue	0.82	0.92	0.22	0.74	0.81	0.19
Tillage × residue	0.13	0.49	0.84	0.11	0.43	0.16

<sup>a</sup> Italic font is used to highlight probabilities  $\leq 0.05$ .

PT had significantly later (4 years) or the same (1993 and 1995), beginning date of seedling emergence as NT (Fig. 1 and Table 2). Similar results were observed for date of 50% seedling emergence, except 2 years (1993 and 1996) just missed being significant at the 5% level ( $p = 0.06$  and  $0.09$ , respectively). However, the beginning of seedling emergence or date of 50% emergence was not well correlated with final number of seedlings emerging, as significantly more seedlings occurred in NT than PT in the first 4 years, but no difference occurred in the last 2 years. NT also had lower standard errors of the mean in final number of seedlings emerged than PT (data not shown). In years where PT treatments had delayed emergence (e.g., 1996), emergence was considerably more variable than in NT plots.

Seedling emergence is mostly determined by temperature and water. Considering the effects of temperature first, we evaluated seedling emergence as a function of thermal time or GDDs. As expected, statistical and graphical results for using air temperature above the canopy to calculate GDD were identical to using calendar day (results not shown) because air temperature above the canopy was the same for all treatments.

Soil temperature at 2–3 cm depth (near the seeding depth) to calculate GDD had significant interaction between tillage and residue level for the beginning of seedling emergence in 1994 and 1997, but never for 50% seedling emergence (results not shown). Residue

treatments had no significant effect for either beginning of seedling emergence or 50% emergence (except 1994), so again only tillage effects will be discussed. For all years but 1996 where soil temperature was measured, similar amounts of soil GDD were required to begin seedling emergence, although plants in PT treatments always required more GDD than in NT treatments to reach the beginning of seedling emergence (Fig. 2). For all years but 1995, plants in NT treatments required significantly fewer GDD to reach 50% seedling emergence than those in PT treatments. The greater GDD required for both beginning of emergence and 50% emergence in PT treatments is likely due to less soil water, and will be discussed later. Neither air nor soil temperature accounted for differences among tillage treatments in the seedling emergence pattern.

One reason that air and soil temperature at 2–3 cm depth had similar results for seedling emergence is that GDD were very similar for air and soil (Table 3). Contrasting soil GDD between PT and NT, the general pattern was that NT treatments accumulated slightly less GDD than PT treatments. For the months of September–November, this amounted to 43 GDD less in NT plots; for the period from September–March, NT treatments accumulated 80 GDD less than PT. The similarity between air and soil temperature at 2–3 cm depth agrees with McMaster and Wilhelm (1998) reported for other sites in the Central Great Plains.

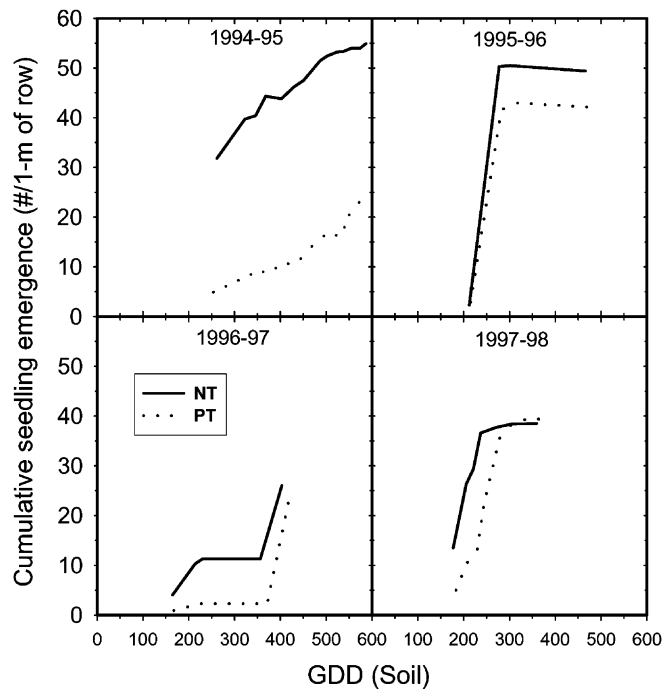


Fig. 2. Seedling emergence based on soil GDDs when pooling residue treatments within tillage treatments. Approximately 55 seeds were planted in 1 m of row.

Since soil temperature was similar to air temperature and both soil and air temperatures were very similar in the PT and NT treatments, the differences in soil water among tillage treatments are likely the cause of the different seedling emergence patterns. Soil water in the seedbed zone (top 15 cm) significantly differed at planting among tillage treatments for 3 out of the 4 years measured (Fig. 3), but never among residue treatments (statistics not shown). Available soil water in the top 15 cm, whether measured gravimetrically by cores or using a neutron probe (which is not recommended at this depth and data not shown), was always less in PT. Visual observations of the top 5 cm in the PT treatments suggested it usually was very dry, so that most water was located from 5 to 15 cm, not where the seed would typically be placed. These results are consistent with other studies (Chevalier and Cihra, 1986; Ellis et al., 1977; Wilhelm et al., 1989). Tillage differences are expected as PT results in the loss of soil water for a variety of reasons including increased evaporation and loss of surface residue mulch.

Contrasting soil water content in the seedbed zone (Fig. 3) with seedling emergence and rainfall (Fig. 1), explanations for observed emergence patterns become clearer. In those years where seedling emergence rates were similar in PT and NT (1993, 1995 and 1997) either soil water was similar and high between treatments (in 1993, sampling included the top 30 cm, so presumably differences between NT and PT near the seed were obscured by including soil water below the seed zone) or rainfall was high after planting (1995 and 1997). In the other 3 years where seedling emergence rates were slower in PT treatments, there was little or no rainfall immediately following planting and soil water was significantly less.

Temperature and soil water interacted to influence emergence. In years with below normal precipitation in September–November (1992, 1994, 1996; Table 1), it seems there was insufficient soil water for germination in the PT plots. In these instances, neither air nor soil temperature accounted well for seedling emergence differences between treatments. Temperature became important after there was sufficient water for

Table 3  
Monthly average GDD summaries for air and soil temperature (2 cm depth) at Colorado State University Horticulture Farm, under NT and PT at the 1R level treatment

Month	GDD																
	14-year mean			1992–1993	1993–1994	1994–1995			1995–1996			1996–1997			1997–1998		
	Air	Soil (PT) <sup>a</sup>	Soil (NT) <sup>a</sup>	Air	Air	Air	Soil (PT)	Soil (NT)	Air	Soil (PT)	Soil (NT)	Air	Soil (PT)	Soil (NT)	Air	Soil (PT)	Soil (NT)
August	603	732	707	590	574	635	–	–	654	748	726	589	754	703	583	694	693
September	454	551	534	515	394	484	–	–	417	512	514	414	561	521	483	579	565
October	292	337	319	364	254	277	298	293	234	323	305	275	351	324	267	375	354
November	106	105	97	58	61	83	59	62	139	156	131	77	123	118	65	82	78
December	34	16	15	1	33	49	7	4	40	37	34	45	10	8	28	12	14
January	34	8	5	6	33	52	5	3	34	9	5	29	10	8	30	6	4
February	59	58	46	14	26	107	72	66	88	63	53	28	43	35	28	54	28
March	138	161	140	161	170	160	169	154	90	142	126	156	176	155	119	157	126
April	239	276	252	223	219	186	229	199	251	316	295	174	251	238	213	307	274
May	402	446	423	415	415	302	331	310	403	474	457	385	502	483	418	478	441
June	530	562	535	504	485	490	473	445	548	581	555	544	654	635	461	539	506
July	636	737	718	606	606	637	654	629	627	714	727	621	808	771	648	773	746
Sum <sup>b</sup>	852	993	950	937	709	844	–	–	790	991	950	766	1035	963	815	1036	997
Sum <sup>c</sup>	1690	1968	1863	1709	1545	1847	–	–	1696	1990	1894	1613	2028	1872	1603	1959	1862
Sum <sup>d</sup>	3497	3989	3791	3457	3270	3462	–	–	3525	4075	3928	3337	4243	3999	3343	4056	3829

<sup>a</sup> Four-year mean for soil GDD.

<sup>b</sup> Sum for months of September–November.

<sup>c</sup> Sum for months of August–March.

<sup>d</sup> Sum for months of August–July.

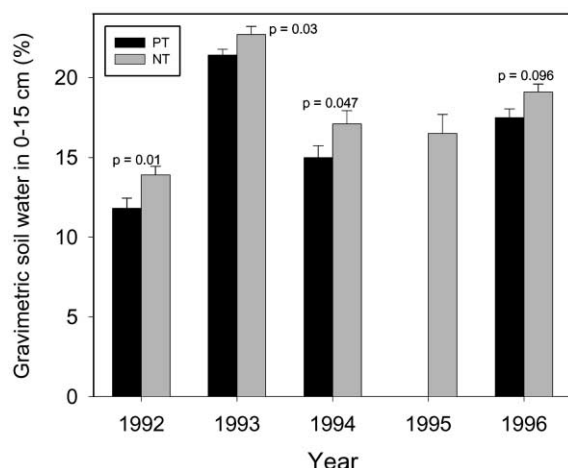


Fig. 3. Gravimetric soil water in the seed zone (0–15 cm) after planting when pooling residue treatments within tillage treatments. Standard error of the mean bars and significance levels (no difference among tillage treatments) are noted above each year. In 1992, a 9.7 mm rainfall event occurred between planting and measurement, soil water estimates for 1993 were for the top 30 cm of soil. Compression of cores in the PT treatments in 1995 prevented collection of samples.

germination (1993 and 1995). Temperature also was very important in 1996 with a late planting date because there was insufficient thermal time in the autumn for processes leading to seedling emergence. There was little accumulation of GDD in the late autumn of 1996 (Table 3), resulting in many of the seedlings emerging in the spring. Small differences leading to germination even a week earlier when late in the autumn can result in significantly more seedlings emerging in the autumn (NT treatments), rather than the spring (PT treatments).

Other factors have been reported to affect seedling emergence under different soil management practices such as disease, weeds, allelopathy and seedbed condition (Aase and Reitz, 1989; Chevalier and Cihra, 1986; Rao and Dao, 1996; Rasmussen et al., 1997; Unger and McCalla, 1980). However, not only are these factors usually explanations for poor stand establishment under no-till conditions, but none of these factors likely played roles in NT treatments having earlier and faster rates of seedling emergence. Pests or disease were not observed in the autumn or winter, and since weeds were not present at seedling emergence, and only 15-month-old wheat straw was

present at seedling emergence, and no allelopathic effect is known for wheat straw, then these factors do not explain differences in treatments. If seedbed condition was the cause, it would be predicted that PT treatments would have been favored in terms of tilth and infiltration over NT treatments at the time of seeding.

Soil management practices are expected to influence soil conditions, particularly water and temperature (Aiken et al., 1997; Greb, 1980; McMaster et al., 2000; Van Doren and Allmaras, 1978), and these conditions interacting with weather at planting will result in variable seedling emergence patterns. However, the degree and direction of changes in soil conditions depends on the system (e.g., humid vs. semiarid) and time of year (e.g., autumn vs. spring). Although we observed highly variable seedling emergence patterns, residue level had very little effect on seedling emergence patterns, but PT clearly tended to delay seedling emergence and reduce the number of seedlings that emerged. Differences between tillage treatments were not due to changes in soil temperature, and this agrees with the results from other sites in the Central Great Plains (McMaster and Wilhelm, 1998). Rather, PT altered soil conditions through evaporative loss of soil water in the plow zone. In years with low rainfall after planting soil water levels were either insufficient for germination or at levels where germination rates were slower.

Because PT reduces soil water in the seedbed zone for many reasons, and this is the critical factor for seedling emergence, rainfall after the PT operations is often essential to supply adequate soil water for germination in semiarid systems such as the Central Great Plains. However, rainfall is highly variable in the Central Great Plains, which introduces additional risk to farmers using PT by depending on adequate rainfall for germination and emergence. To evaluate the degree of risk, we estimated the amount of soil water necessary for germination and the probability of rainfall events sufficient to provide the necessary soil water levels for germination given two different levels of soil water at planting, 30 and 40% water filled pore space (Table 4). Since planting often occurs in the last half of September, only one rainfall event on average (0.7 if 1995 is not included) occurs during this period sufficient for germination (if 30% water filled pore space at planting is assumed). If this

Table 4

Number of rainfall events occurring that would raise soil water from either 30 or 40% water filled pore space to  $-0.033$  MPa (field capacity)

Year	30% <sup>a</sup>				40% <sup>a</sup>			
	1–15 September	16–30 September	1–15 October	16–31 October	1–15 September	16–30 September	1–15 October	16–31 October
1986	2	0	2	1	2	1	2	2
1987	0	0	0	1	0	0	0	1
1988	2	0	0	0	3	1	0	0
1989	2	0	0	0	3	0	0	1
1990	0	2	1	0	1	3	1	0
1991	0	1	0	1	1	1	1	2
1992	0	0	1	0	0	0	1	0
1993	2	1	0	2	2	1	0	2
1994	0	0	2	1	0	1	2	1
1995	0	4	0	0	0	5	1	0
1996	1	1	0	0	1	2	0	0
1997	0	3	1	0	0	5	1	1
1998	1	1	2	3	1	1	2	3
Mean	0.8	1.0	0.7	0.7	1.1	1.6	0.9	1.0

<sup>a</sup> Water filled pore space.

event occurs immediately after planting, then little differences in seedling emergence would be expected among tillage treatments. As the delay increases, increasingly greater difference among tillage treatments would be predicted, particularly since NT will have more water in the seed zone. In years where PT treatments tended to have delayed seedling emergence (e.g., 1992, 1994 and 1996), only 1994 had one rainfall event (8 days after planting) during the half-month period after planting sufficient for germination (assuming 40% water filled pore space after tillage), and no rainfall events occurred for all 3 years if 30% water filled pore space is assumed after tillage. Therefore, the probability of adequate rainfall for germination to occur is not high for the Central Great Plains. Extrapolating these results to more intensive tillage operations during the fallow period would suggest that as each tillage operation depletes the soil water in the plow zone, the dependency on rainfall after planting becomes even more critical. Greater rainfall events will be required as soil water levels decrease, and the probability of these events decreases considerably. Farmers will have to alter management practices such as using subsurface tillage practices that conserve water and deeper planting depth to allow for depleted water in the plow zone.

### 3.2. Autumn development and growth

Differences in seedling emergence between treatments and years were also reflected in autumn development and growth. Total aboveground weight in the late autumn was greater in the NT treatments for all years except 1995–1996 (Fig. 4), and it was statistically greater for the first 3 years (Table 5). The same patterns were found for partitioning aboveground biomass between leaf blade and non-leaf blade (stem, leaf sheath and crown tissue) components as for total aboveground weight (Table 5). Wheat biomass did not differ among treatments if the final number of seedlings emerged in the autumn was similar among treatments.

Shoot number (main stem + tillers) was always greater in the NT plots (Fig. 5), and significantly greater ( $p < 0.06$ ) for 1992, 1994, 1995 and 1996 (Table 5). Occasionally (e.g., 1992 and 1994), the greater shoot number is largely because more seedlings emerged. However, seedlings that emerged shortly after planting accumulate more GDD and therefore produce more leaves. As more leaves appear, the opportunity for more tillers to appear increases (Klepper et al., 1984), which also explains the greater tillering observed in NT plots. For example, if a seedling emerges 1 week earlier in September and

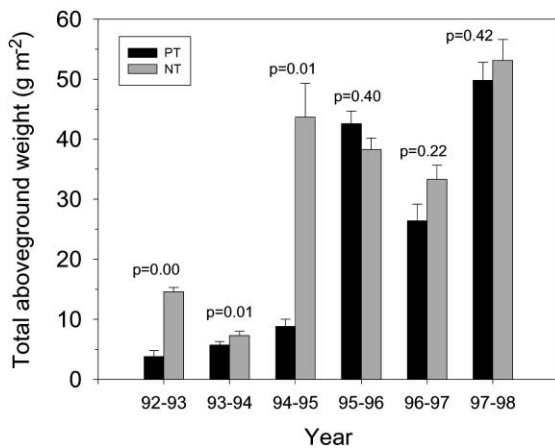


Fig. 4. Total aboveground weight at late autumn or early winter when pooling residue treatments within tillage treatments. Standard errors of the mean bars and significance levels (no difference among tillage treatments) are noted in the figure.

assuming a mean daily temperature of 15.0 °C (Table 1), then 105 more GDD will be available for leaf appearance. Since typically about 108 GDD are required to produce one leaf for winter wheat cultivars grown in this region (McMaster and Wilhelm, 1995), then this results in about one more leaf that can be

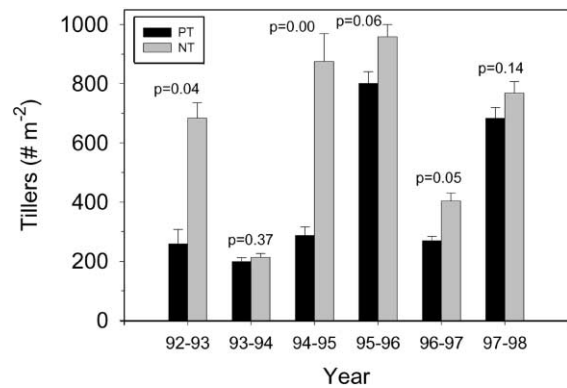


Fig. 5. Tiller density at late autumn or early winter when pooling residue treatments within tillage treatments. Standard errors of the mean bars and significance levels (no difference among tillage treatments) are noted above each year.

produced. Axillary buds formed by each leaf can produce new tillers.

Because of more favorable emergence conditions, canopy development was greater in NT. There are a number of important benefits of greater canopy development in the autumn, including reduced winter kill, better soil erosion protection (Hagen, 1996; McMaster and Wilhelm, 1997a), reduced evaporation (Aiken

Table 5

Significance level (no difference among tillage treatments) for autumn (or earliest sampling date) plant density, shoot number and biomass

Tillage/residue	Parameters	Sampling date					
		5 November 1992	3 January 1993	21 December 1994	5 December 1995	12 May 1997	16 December 1997
Tillage	# plants	0.53	0.24	<i>0.01<sup>a</sup></i>	0.88	0.09	0.75
	# shoots	<i>0.04</i>	0.37	<i>0.00</i>	0.06	<i>0.05</i>	0.14
	Blade weight	–	0.02	<i>0.01</i>	0.59	0.17	0.50
	Non-blade weight <sup>b</sup>	–	0.02	<i>0.01</i>	0.23	0.44	0.29
	Total weight	<i>0.00</i>	<i>0.01</i>	<i>0.01</i>	0.40	0.22	0.42
Residue	# plants	0.80	<i>0.04</i>	0.89	0.10	0.80	0.64
	# shoots	0.24	<i>0.00</i>	<i>0.03</i>	0.07	0.96	0.71
	Blade weight	–	0.11	0.08	<i>0.05</i>	0.98	0.87
	Non-blade weight <sup>b</sup>	–	<i>0.04</i>	0.11	0.64	0.39	0.86
	Total weight	0.28	0.07	0.09	0.13	0.83	0.88
Tillage × residue	# plants	0.47	0.23	0.43	0.42	0.89	0.37
	# shoots	0.46	<i>0.03</i>	0.07	0.15	0.68	0.27
	Blade weight	–	0.73	0.20	0.10	0.66	0.09
	Non-blade weight <sup>b</sup>	–	0.76	0.33	0.66	0.40	0.07
	Total weight	0.57	0.76	0.25	0.20	0.58	0.08

<sup>a</sup> Italic font is used to highlight probabilities ≤0.05.

<sup>b</sup> Non-blade tissue is stem + leaf sheath + crown weight.

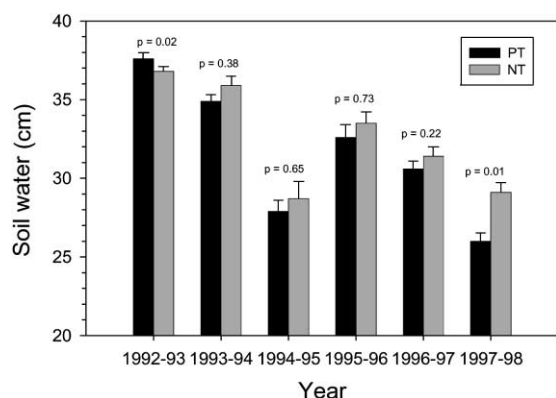


Fig. 6. Soil water in profile (0–122 cm) at spring green-up (normally beginning of March) when pooling residue treatments within tillage treatments. Standard errors of the mean bars and significance levels (no difference among tillage treatments) are noted above each year.

et al., 1997; Van Doren and Allmaras, 1978), greater snow catch which further reduces winter kill as well as increases soil water in the profile at the beginning of spring growth (Greb, 1980), and a positive relationship with yield (Chevalier and Ciha, 1986; Gan et al., 1992; Gan and Stobbe, 1996). We found that in all years except 1993, more total water (mean = 1.3 cm) was available in the soil profile (0–122 cm) at the beginning of spring green-up (near 1 March) in the NT plots than in the PT plots (Fig. 6), although rarely was it significantly greater.

### 3.3. Yield

Despite earlier and greater seedling emergence and greater autumn development and growth in the NT treatment, NT plots also had greater available soil water in the spring. Greater soil water during spring, near jointing (Feekes growth stage 6.0, Large, 1954), which occurred about 6 May in our experiment, is important for determining most of the yield potential (McMaster, 1997). Since the main yield component in the Central Great Plains is spike number per unit area (McMaster et al., 1994), reduced water stress at jointing should decrease tiller abortion. Tiller survival will be increased further if more leaves have been produced by jointing as a result of earlier seedling emergence (McMaster et al., 1991). Greater soil water near jointing should also enhance spikelet and floret primordia initiation, the next major yield components

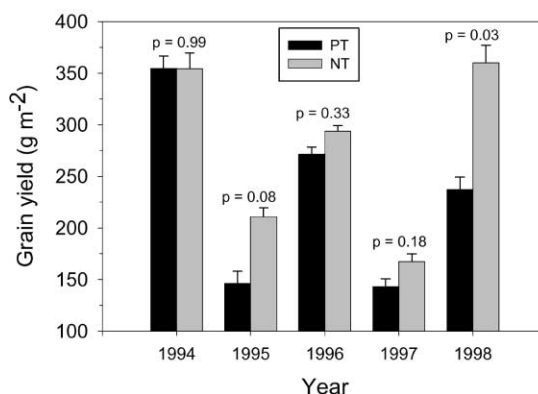


Fig. 7. Grain yield when pooling residue treatments within tillage treatments. Standard errors of the mean bars and significance levels (no difference among tillage treatments) are noted above each year.

in the Central Great Plains, which occurs during spring (McMaster et al., 1994).

Therefore, it follows that earlier and greater seedling emergence found in NT treatments leading to greater autumn canopy development and more spring soil water should be positively correlated with greater yield. Indeed, in years with faster seedling emergence (1992, 1994, 1996 and 1997) and years with greater seedling emergence (1992, 1993, 1994 and 1995), yield was increased (Fig. 7). Gan et al. (1992) and Gan and Stobbe (1996) found that earlier emerging wheat plants formed more spike-bearing tillers and had greater yield than plants emerging later. Chevalier and Ciha (1986) also observed that earlier emerging plants with greater earlier growth resulted in higher yields. We also found that greater soil water in the spring in the NT treatments (Fig. 6) was positively correlated (but not significant at  $\alpha = 0.05$ ) with yield (Fig. 7), except for 1993 when there was no yield difference. No correlation was found between total yearly precipitation (Table 1) and final yield (Fig. 7,  $p = 0.88$ ).

## 4. Conclusions

While PT may aid in weed control and is thought to provide good seedbed conditions for seedling emergence and growth, because of the loss of soil water from the seedbed after tillage, this management practice is riskier than adopting NT in semiarid wheat

production regions such as the Central Great Plains. If sufficient rainfall occurs after planting to stimulate germination, then seedling emergence in PT will be similar to NT. However, in dry conditions PT practices will result in slower and more spatially variable seedling emergence rates and fewer seedlings. Earlier and greater seedling emergence results in greater autumn growth (e.g., biomass, number of leaves and tillers). Greater spring soil water was also observed in the NT plots. Greater spring soil water at the growth stage of jointing increases tiller survival, leading to higher yields by influencing the main yield component, number of spikes per unit area. When the additional soil and water conservation benefits of NT are considered, this 6-year study indicates that minimizing pre-planting tillage operations in the Central Great Plains would maximize yield and conservation benefits.

## Acknowledgements

Special thanks to R. Erskine, T. Leonard, M. Murphy, L. Sherrod and K. Stonaker for technical assistance in the field and laboratory.

## References

- Aase, J.K., Reitz, L.L., 1989. Effects of tillage practices and crop sequence on spring grain production in the Northern Great Plains. *Appl. Agric. Res.* 4, 30–36.
- Aiken, R.M., Flerchinger, G.N., Farahani, H.J., Johnsen, K.E., 1997. Energy balance simulation for surface soil and residue temperatures with incomplete cover. *Agron. J.* 89, 405–416.
- Bond, J.J., Power, J.F., Willis, W.O., 1971. Tillage and crop residue management during seedbed preparation for continuous spring wheat. *Agron. J.* 63, 789–793.
- Chevalier, P.M., Ciha, A.J., 1986. Influence of tillage on phenology and carbohydrate metabolism of spring wheat. *Agron. J.* 78, 296–300.
- Ciha, A.J., 1982. Yield and yield components of four spring wheat cultivars grown under three tillage systems. *Agron. J.* 74, 317–320.
- Dao, T.H., Nguyen, H.T., 1989. Growth response of cultivars to conservation tillage in a continuous wheat cropping system. *Agron. J.* 81, 923–929.
- Ellis, F.B., Elliott, J.G., Barnes, B.T., Howse, K.R., 1977. Comparison of direct drilling, reduced cultivation and ploughing on the growth of cereals. 2. Spring barley on a sandy loam soil: soil physical conditions and root growth. *J. Agric. Sci. Camb.* 89, 631–642.
- Gan, Y., Stobbe, E.H., 1996. Mainstem leaf stage and its relation to single plant grain yield in spring wheat. *Crop Sci.* 36, 628–632.
- Gan, Y., Stobbe, E.H., Moes, J., 1992. Relative date of wheat seedling emergence and its impact on grain yield. *Crop Sci.* 32, 1275–1281.
- Greb, B.W., 1980. Snowfall and its potential management in the semi-arid Central Great Plains. USDA-SEA Agricultural Reviews and Manuals ARM-W-18. US Government Printing Office, Washington, DC.
- Hagen, L.J., 1996. Crop residue effects on aerodynamic processes and wind erosion. *Theor. Appl. Climatol.* 54, 39–46.
- Haun, J.R., 1973. Visual quantification of wheat development. *Agron. J.* 65, 116–119.
- Klepper, B., Belford, R.K., Rickman, R.W., 1984. Root and shoot development in winter wheat. *Agron. J.* 76, 117–122.
- Large, E.C., 1954. Growth stages in cereals. *Plant Pathol.* 3, 128–129.
- McMaster, G.S., 1997. Phenology, development, and growth of the wheat (*Triticum aestivum* L.) shoot apex: a review. *Adv. Agron.* 59, 63–118.
- McMaster, G.S., Aiken, R.M., Nielsen, D.C., 2000. Optimizing wheat harvest cutting height for harvest efficiency and soil and water conservation. *Agron. J.* 92, 1104–1108.
- McMaster, G.S., Klepper, B., Rickman, R.W., Wilhelm, W.W., Willis, W.O., 1991. Simulation of aboveground vegetative development and growth of unstressed winter wheat. *Ecol. Model.* 53, 189–204.
- McMaster, G.S., Smika, D.E., 1988. Estimation and evaluation of winter wheat phenology in the Central Great Plains. *Agric. For. Meteorol.* 43, 1–18.
- McMaster, G.S., Wilhelm, W.W., 1995. Accuracy of equations predicting the phyllochron of wheat. *Crop Sci.* 35, 30–36.
- McMaster, G.S., Wilhelm, W.W., 1997a. Conservation compliance credit for winter wheat fall biomass and implications for grain production. *J. Soil Water Conserv.* 52, 358–362.
- McMaster, G.S., Wilhelm, W.W., 1997b. Growing degree-days: one equation, two interpretations. *Agric. For. Meteorol.* 87, 289–298.
- McMaster, G.S., Wilhelm, W.W., 1998. Is using soil temperature better than air temperature for predicting winter wheat phenology? *Agron. J.* 90, 602–607.
- McMaster, G.S., Wilhelm, W.W., Bartling, P.N.S., 1994. Irrigation and culm contribution to yield and yield components of winter wheat. *Agron. J.* 86, 1123–1127.
- Rao, S.C., Dao, T.H., 1992. Fertilizer placement and tillage effects on nitrogen assimilation by wheat. *Agron. J.* 84, 1028–1032.
- Rao, S.C., Dao, T.H., 1996. Nitrogen placement and tillage effects on dry matter and nitrogen accumulation and redistribution in winter wheat. *Agron. J.* 88, 365–371.
- Rasmussen, P.E., Rickman, R.W., Klepper, B.L., 1997. Residue and fertility effects on yield of no-till wheat. *Agron. J.* 89, 563–567.
- SAS Institute, 1991. SAS Language and Procedures, Vers. 6.0. SAS Institute, Cary, NC.

- Smika, D.E., Ellis Jr., R., 1971. Soil temperature and wheat straw mulch effects on wheat plant development and nutrient concentration. *Agron. J.* 63, 388–391.
- Studdert, G.A., Wilhelm, W.W., Power, J.F., 1994. Imbibition response of winter wheat to water-filled pore space. *Agron. J.* 86, 995–1000.
- Unger, P.W., McCalla, T.M., 1980. Conservation tillage systems. *Adv. Agron.* 33, 1–58.
- Van Doren Jr., D.M., Allmaras, R.R., 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. In: Oschwald, W.R. (Ed.), *Crop Residue Management Systems*. ASA Special Publication 31. ASA, CSSA, and SSSA, Madison, WI, pp. 49–83.
- Wilhelm, W.W., Bouzerzour, H., Power, J.F., 1989. Soil disturbance–residue management effect on winter wheat growth and yield. *Agron. J.* 81, 581–588.
- Wilhelm, W.W., McMaster, G.S., Rickman, R.W., Klepper, B., 1993. Aboveground vegetative development and growth of winter wheat as influenced by nitrogen and water availability. *Ecol. Model.* 68, 183–203.